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More Accurate Estimators of Noise Level and TEOAE/noise in TEOAE Tests

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Abstract-**This study proposed new estimators to estimate the noise level and TEOAE/noise, which are important indicators of the reliability of the recorded TEOAEs. Fifteen normal ears were tested to evaluate the performance. Results showed that the standard deviations of the proposed estimators were smaller than those of typical estimators.**

Ⅰ. Introduction

Transiently-evoked otoacoustic emissions (TEOAEs) are the acoustic signals produced by the inner ear in response to transient acoustic stimuli. They can be recorded in the external auditory canal with a sensitive microphone [1]. Recently, TEOAE tests have been widely used for newborn hearing screening.

TEOAEs are weak signals and easily contaminated by background noise. Hence, like processing some weak signals embedded in noise [2], [3], the estimation of the reliability of the recorded TEOAEs is very critical for further analysis. Because noise level and signal-to-noise ratio (SNR) were shown to be important parameters that closely relate with the reliability [2], [3], accurate estimation of these parameters are necessary for accurate estimation of the reliability.

This study proposes estimators [3] to estimate the noise level and TEOAE/noise (an estimation of SNR) [4] more accurately. To evaluate the performance, the standard deviations and the means of the proposed estimators were compared with those of typical estimators.

Ⅱ. Materials and Methods

A. TEOAE Acquisition

Our own acquisition system for the TEOAE signals was developed. This acquisition system included a personal computer (PC) equipped with Intel Pentium CPU, a Loughborough Sound Images' (LSI) PC/C32 control board and an Etymotic Research's ER-10C acoustic-electric transformation system. A human-machine interface, which was programmed with the Borland C++ Builder software, was established on the personal computer.

Regarding the acquisition of TEOAE signals, we referred to the procedure adopted in previous studies [5]. During the acquisition, the following settings were used. (1) The 80-μs acoustic impulses (clicks) with intensity of 80 dB sound pressure level (SPL) were used to stimulate the cochlea at a rate of 50/sec, and the derived nonlinear response (DNLR) [5] method was used. (2) The ER-10C system was set with the gain of 40 dB. (3) The evoked responses to the acoustic impulses were filtered by a fourth-order low-pass filter with cutoff frequency of 10.6 kHz and with unity gain. (4) The filtered evoked responses were then sampled at a rate of 25 kHz, and 512 samples were obtained per response. (5) The samples were windowed using the 2.5 ms-20.5 ms response window which had 2.5 ms cosine onset and offset, and were filtered by a digital bandpass filter with the bandwidth from 600 to 6000 Hz. (6) The noise rejection threshold was set at 50 dB SPL. The four evoked responses associated to each set of the four-clicks stimuli were averaged for every four-clicks set, and each resulting averaged response will be referred to as the subaveraged response throughout the text. These subaveraged responses were alternately sent to two different buffers (A and B), and the TEOAE acquisition for individual ear was complete after each buffer collected 256 subaveraged responses. The all evoked responses for this study were collected from 15 normal ears of eight adults, and they were measured within general laboratory without sound proof.

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B. Estimators of noise level and TEOAE/noise

For individual ear, there were total 512 subaveraged responses in A and B buffer. A pair of TEOAE signals for an ear could be obtained by averaging the 256 subaveraged responses in the two buffers individually. Typical estimators of TEOAE level, noise level, and TEOAE/noise were using the following formulas [4], [5]. In these formulas, *A(t)* and *B(t)* represents the paired signals in buffer A and buffer B respectively, where $t = 1,2,\cdots T(512)$ represents different samples.

1. TEOAE level: The TEOAE level is defined as the root mean square (RMS) of the average of the corresponding paired signals.
$$TEOAE\ level = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(\frac{A(t)+B(t)}{2}\right)^2}$$
2. Noise level: Noise level is defined as the RMS of the estimated noise, which is obtained by dividing the difference of the paired signals by two.
$$Noise\ level = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(\frac{A(t)-B(t)}{2}\right)^2},$$
3. TEOAE/noise: TEOAE/noise is defined by dividing TEOAE level by noise level. It is an estimation of SNR.

From the formulas above, the estimated values are influenced seriously by the waveform of *A(t)* and *B(t)*, which are the averages of 256 subaveraged responses, respectively. Comparing with typical estimators, this study proposed the estimators [3] to estimate noise level and

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TEOAE/noise more accurately. The estimations were performed using the below equations. In these equations, each subaveraged response is symbolized as $X_j(t)$, where t = 1,2,⋯512 indicates different samples of a subaveraged response and j = 1,2, ⋯ 512 represents different subaveraged response. These equations are

$$\hat{\sigma}_N^2 = \frac{1}{T(J-1)} \sum_{j=1}^{J} \sum_{t=1}^{T} \left[X_j(t) - \bar{X}(t) \right]^2,$$

$$\hat{\sigma}_S^2 = \frac{1}{T} \sum_{t=1}^{T} \bar{X}^2(t) - \left(\hat{\sigma}_N^2 / J \right),$$

$$\hat{\sigma}_X^2 = \frac{1}{JT} \sum_{j=1}^{J} \sum_{t=1}^{T} X_j^2(t),$$

$$\text{where} \quad \bar{X}(t) = (1/J) \sum_j X_j(t)$$

These equations satisfy the algebraic equality $\hat{\sigma}_X^2 = \hat{\sigma}_S^2 + \hat{\sigma}_N^2$. By these equations, the estimated noise level is $\sqrt{\hat{\sigma}_N^2 / J}$ and the estimated TEOAE/noise is $\sqrt{J \hat{\sigma}_S^2 / \hat{\sigma}_N^2}$. By the way, the averaged signals $A(t)$ and $B(t)$ in the two buffers can be expressed using $X_j(t)$ as

$$A(t) = \sum_{j=1}^{J/2} X_{2j-1}(t), \text{ and } B(t) = \sum_{j=1}^{J/2} X_{2j}(t).$$

C. Performance Evaluation of the Estimators

To evaluate the performance of the proposed estimators, fifteen normal ears were tested in the study. For each ear, a set of 512 subaveraged responses was obtained as the procedure in section A. The TEOAE signals for the ear were obtained by selecting 128 subaveraged responses from the associated set and averaging them. Because the background noise levels could be various during the acquisition time of the 512 subaveraged responses, the 128 subaveraged responses for TEOAE signals were selected using the following criterion. (1) The total 512 subaveraged responses for each set were equally divided into 128 blocks according to their sequence. (2) For each block, two different subaveraged responses were randomly selected and stored into two buffers (A, B), respectively. With the 128 subaveraged responses in each buffer, the noise level and the TEOAE/noise were estimated both by typical estimators and by the proposed estimators. All the procedure was repeated 100 times for each set of 512 subaveraged responses. The means and the standard deviations of the noise level and TEOAE/noise estimators were then calculated, respectively, by the repeated procedure of 100 times.

Ⅲ. RESULTS

Fig. 1 shows the standard deviations of the noise level for 15 normal ears, estimated both by typical estimator and by the proposed estimator. Fig. 2 shows the standard deviations of the TEOAE/noise for 15 normal ears. In these two figures, the means of the typical and the proposed estimators are not shown because there is no obvious difference between them. It could be observed that both noise level and TEOAE/noise have smaller standard deviations when estimated by the proposed estimators.

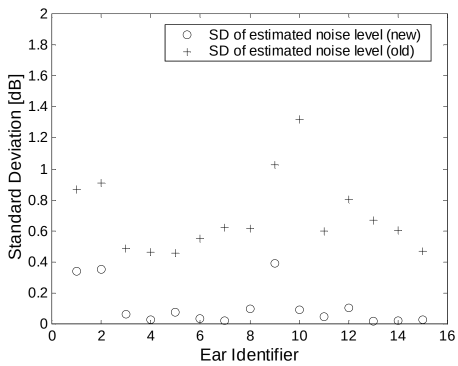

Fig. 1 Standard deviations of the noise level for 15 normal ears, estimated by typical estimator (old) and by the proposed estimator (new).

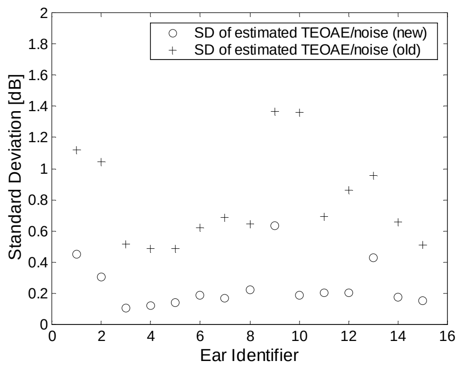

Fig. 2 Standard deviations of the TEOAE/noise for 15 normal ears, estimated by typical estimator (old) and by the proposed estimator (new).

Ⅳ. DISCUSSIONS AND CONCLUSIONS

Results show that the standard deviations of the proposed noise level and TEOAE/noise estimators are smaller than those of the typical estimators.

Noise level and TEOAE/noise are important parameters that closely relate with the reliability of the recorded TEOAE signals. With the improvement of computation power of modern computers, more complicated estimators could be implemented to increase the accuracy of the estimation. It is believed that with these more accurate estimators, the reliability of the recorded TEOAE signals could be increased, and then the accuracy of the diagnosis could be improved much more.

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